The Quest for Bright, Coherent X-Ray
A Personal Story

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ANL
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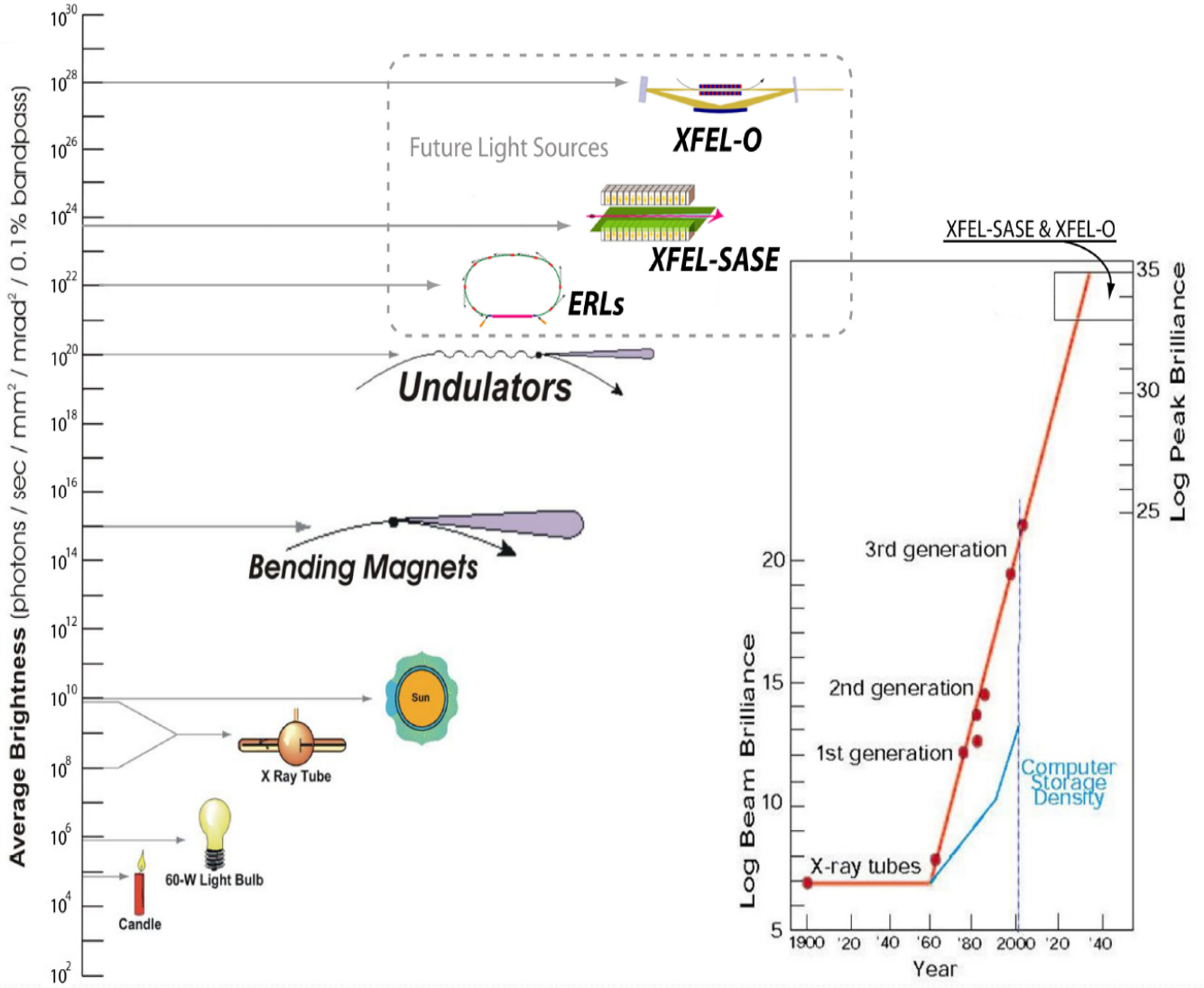
Legend of evolving bright & coherent x-ray sources



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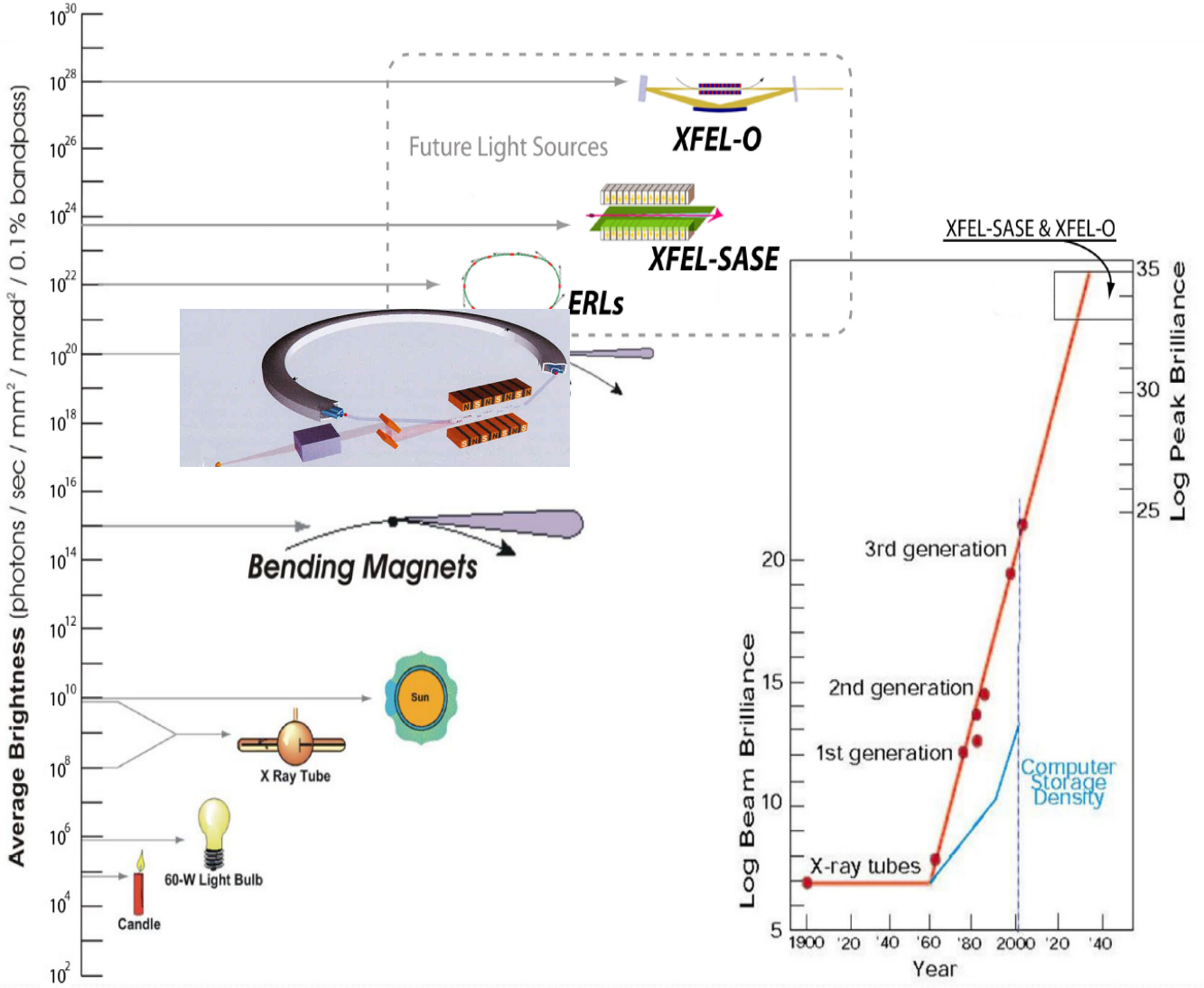

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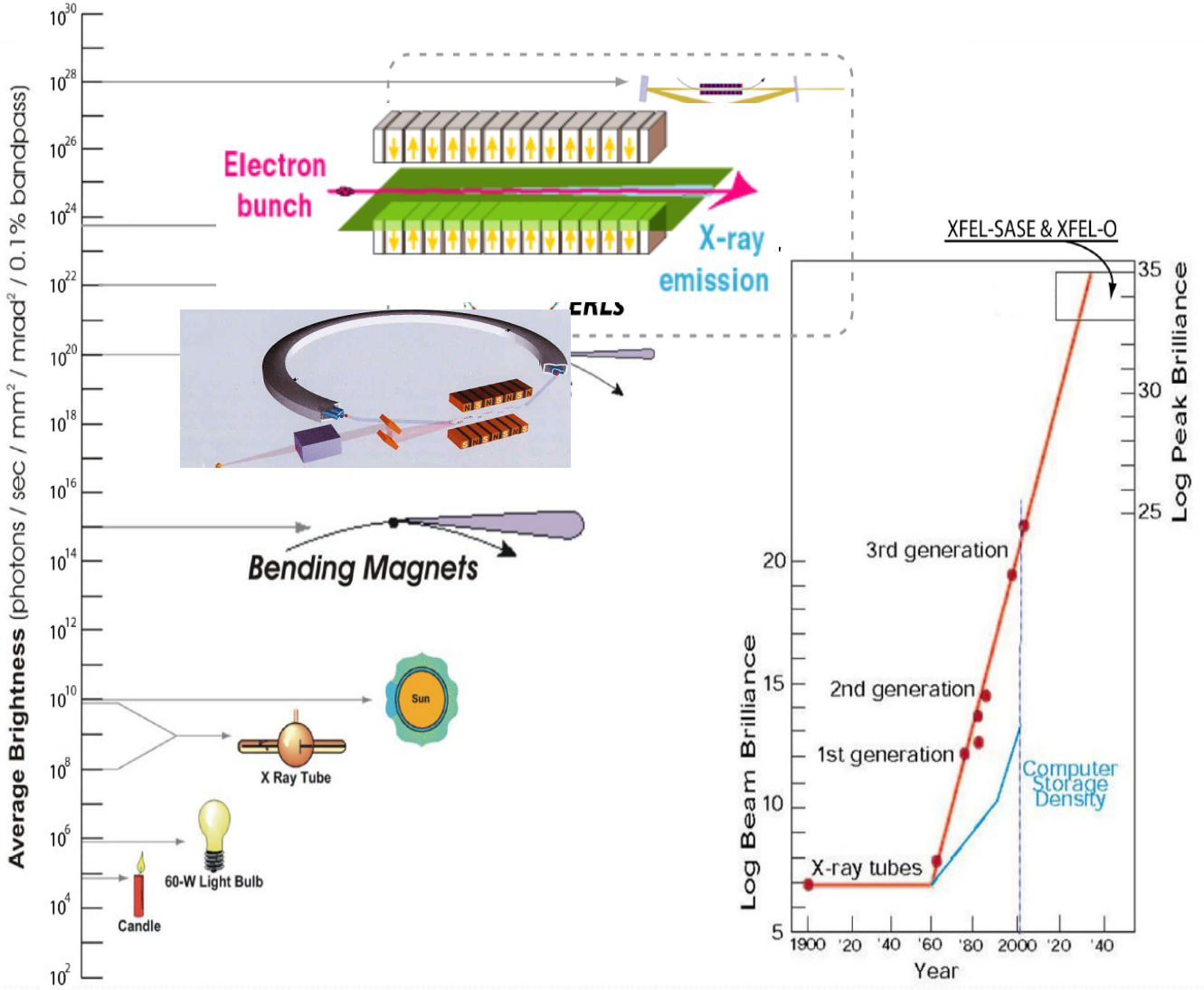

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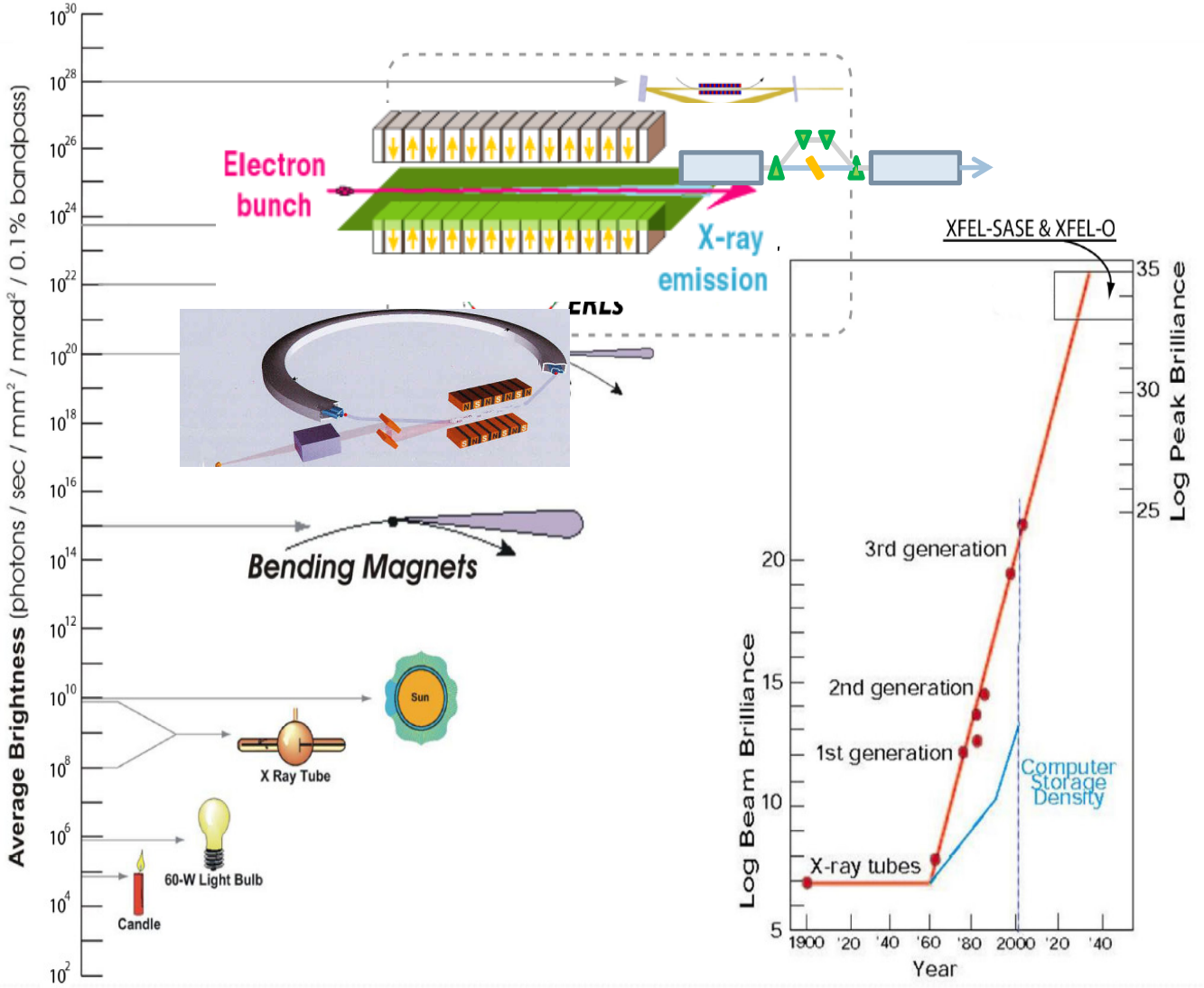

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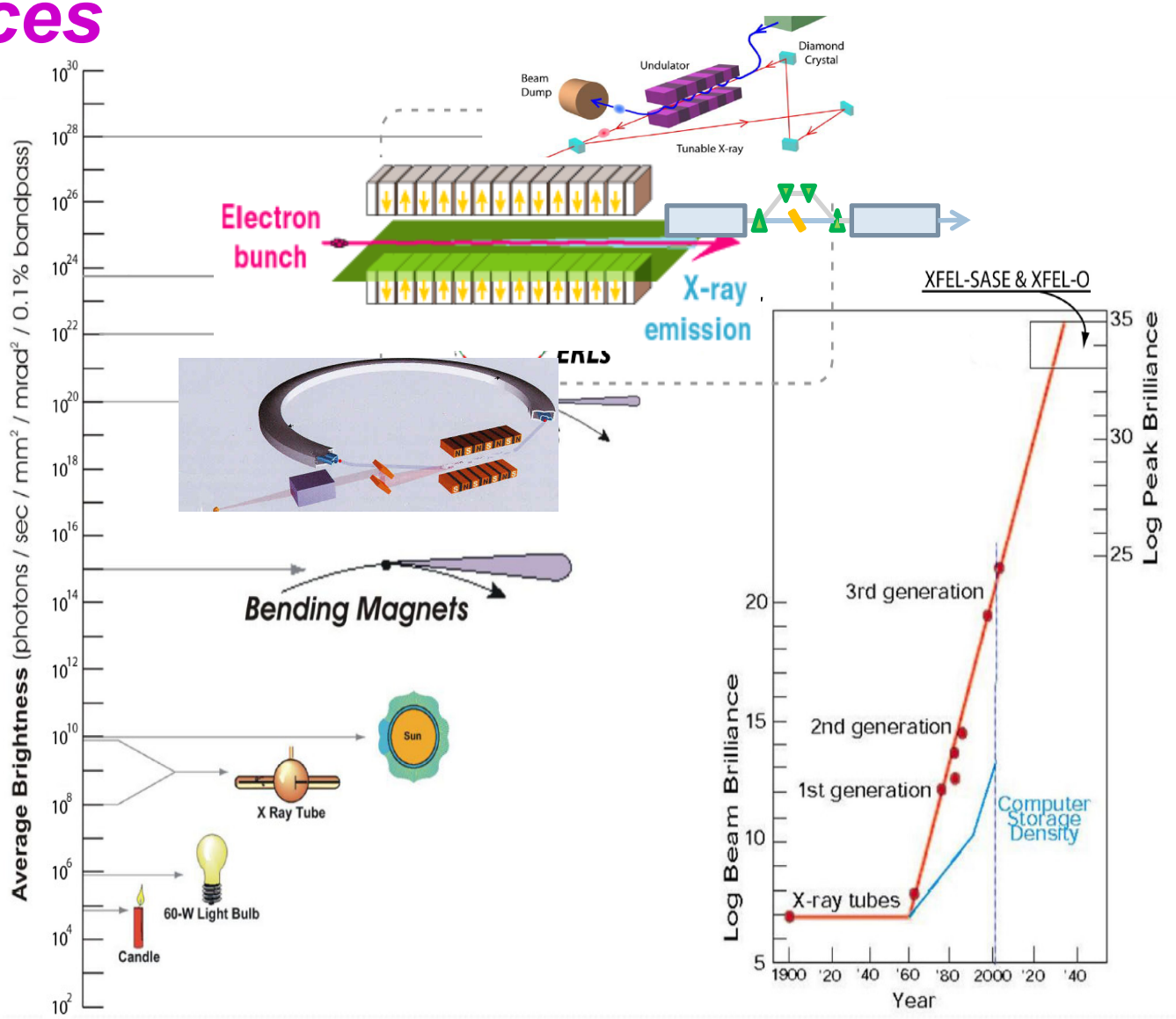

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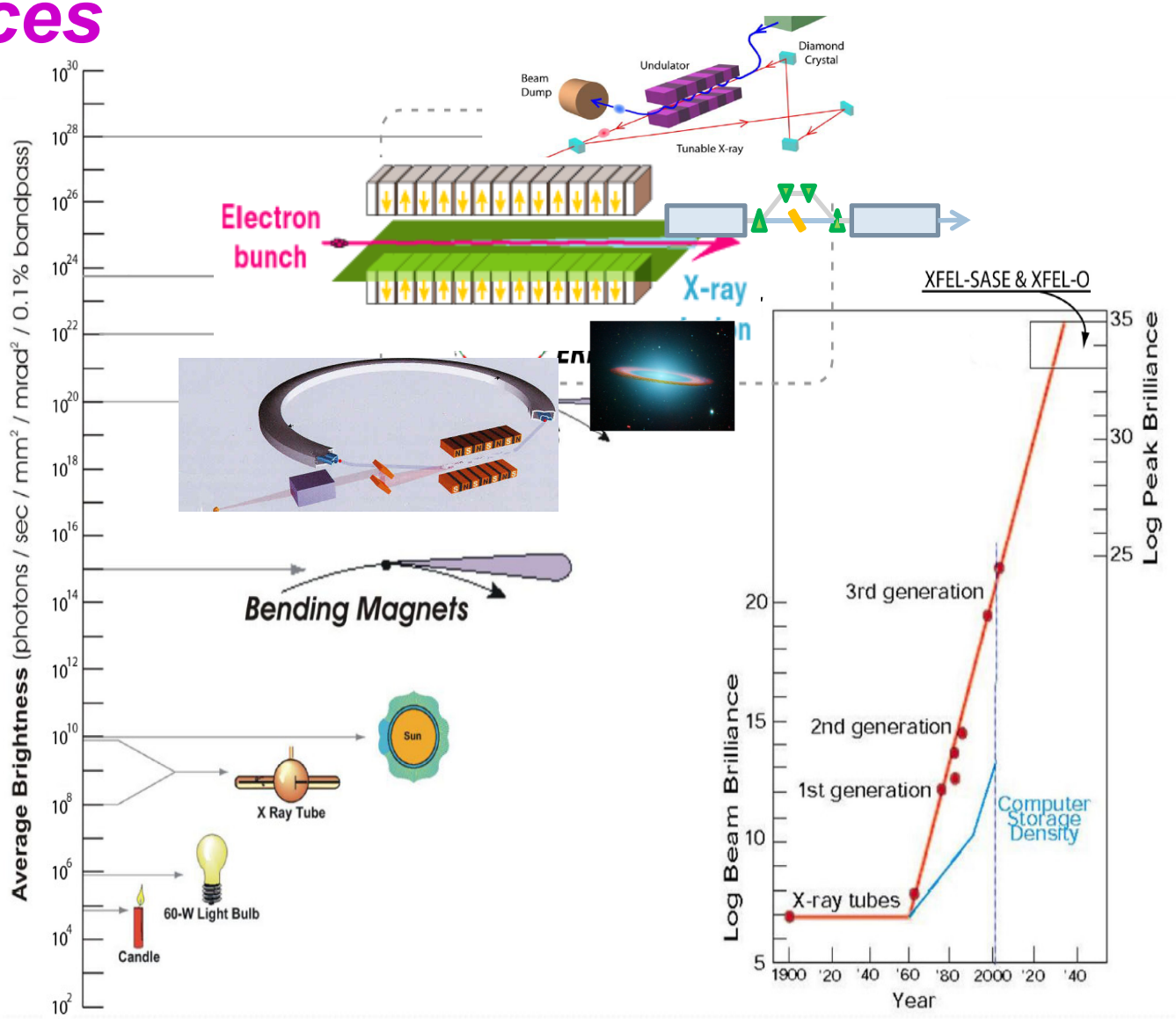
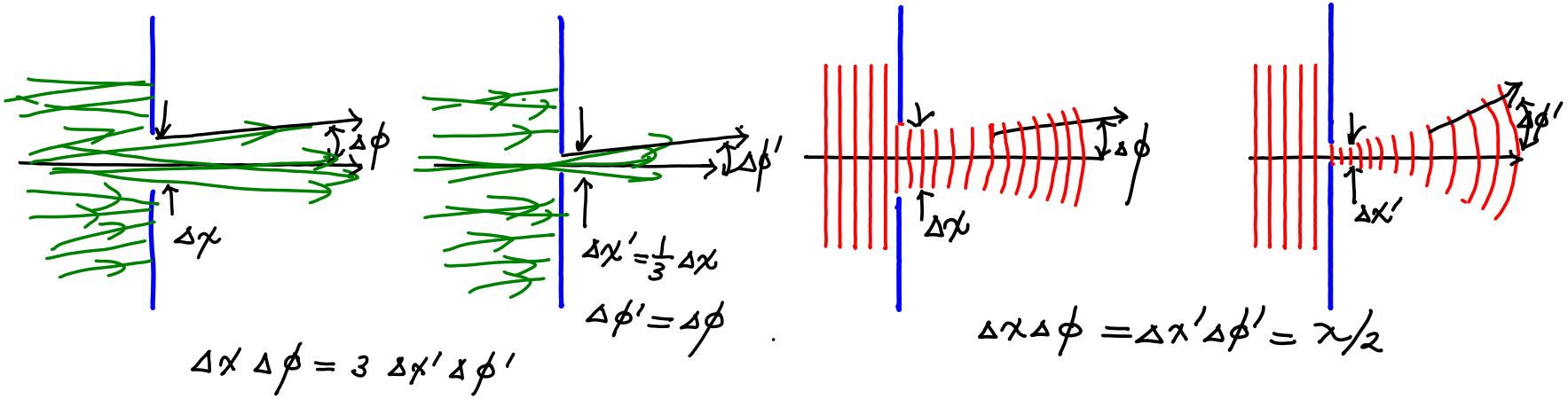
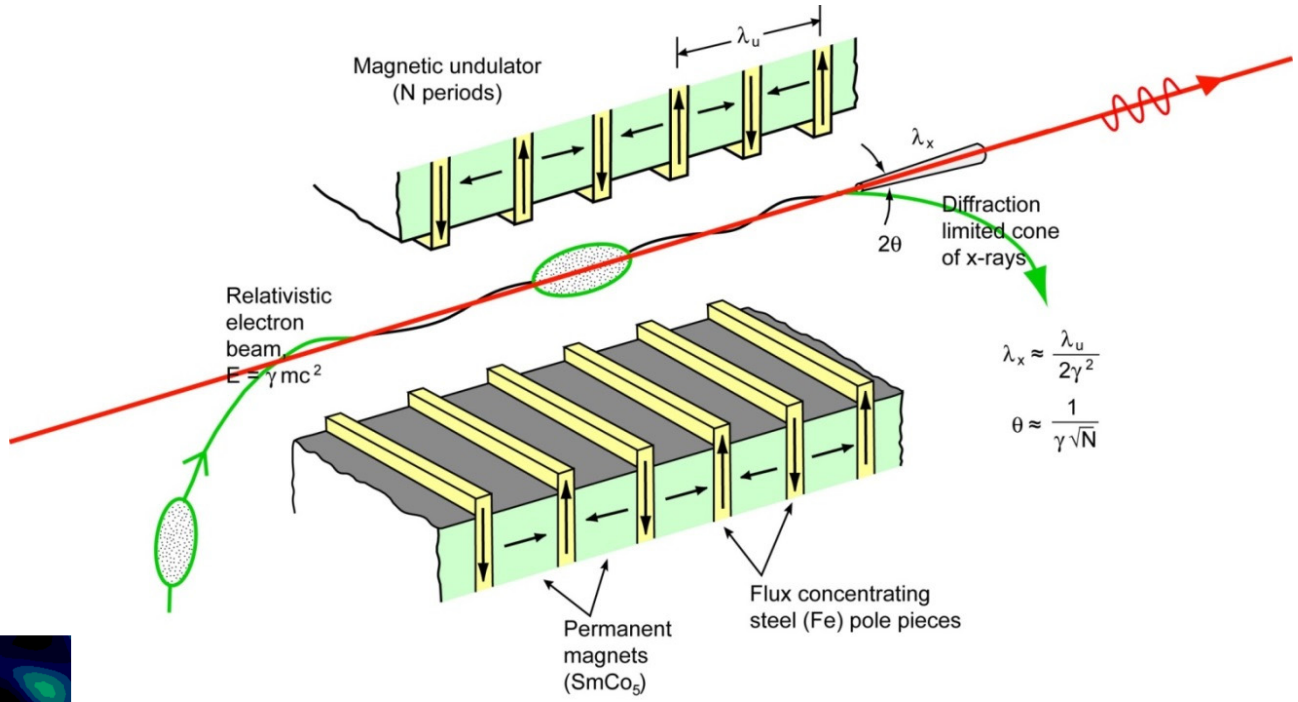


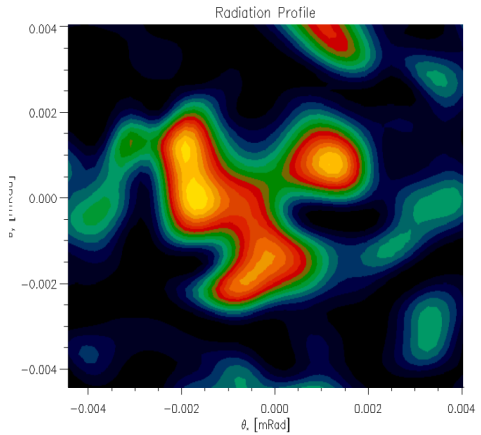
Incoherent e-beam and coherent radiation

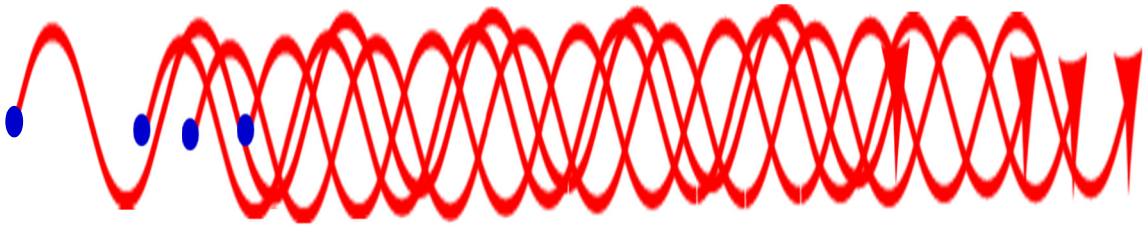


- **The phase space area ($\Delta x \Delta \phi$) of incoherent e-beam can be divided into smaller and smaller area**
- **With coherent beam the phase space area cannot be divided to area smaller than $\Delta x \Delta \phi = \lambda/2$**
- ***A unified description*** **of coherent and incoherent phase space concept is needed for a correct description of brightness, B, for undulator radiation from a collection electrons in a beam**

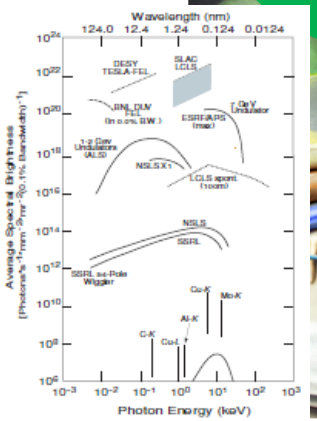
Undulator radiation by a collection of electrons



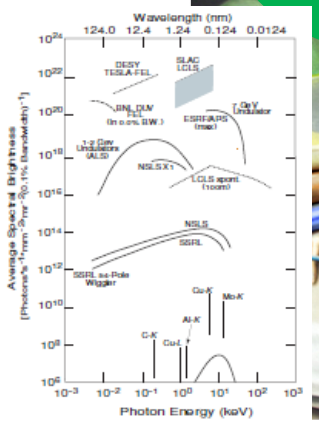


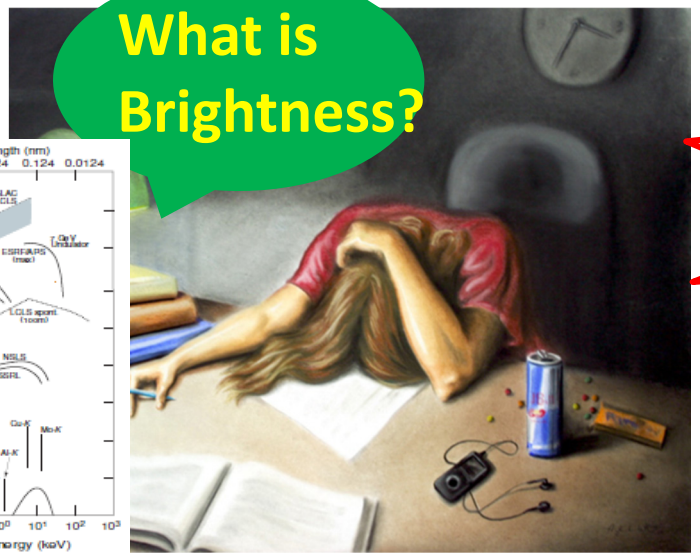


What is Brightness?



$$B(x, \phi; z) = \int dy \exp(iky\phi) \langle E^*(x+y/2;z)\, E(x-y/2;z) \rangle$$





Eureka!!!!!

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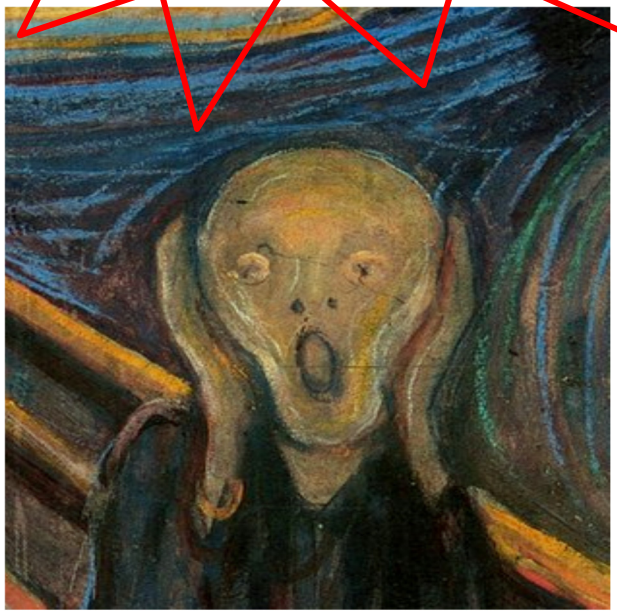
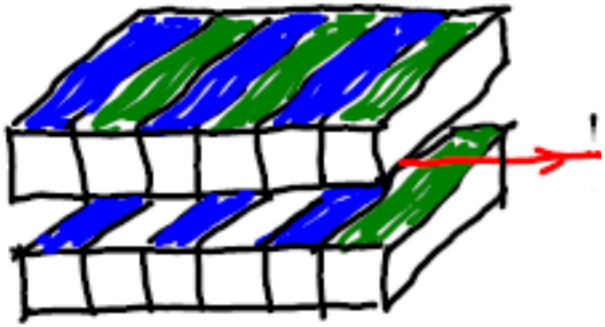


At a seminar at NSLS Marty Blume noted that this was introduced by E. Wigner in 1930s for Quantum statistical mechanics

But it could have practical application for USR undulators

Variable polarization



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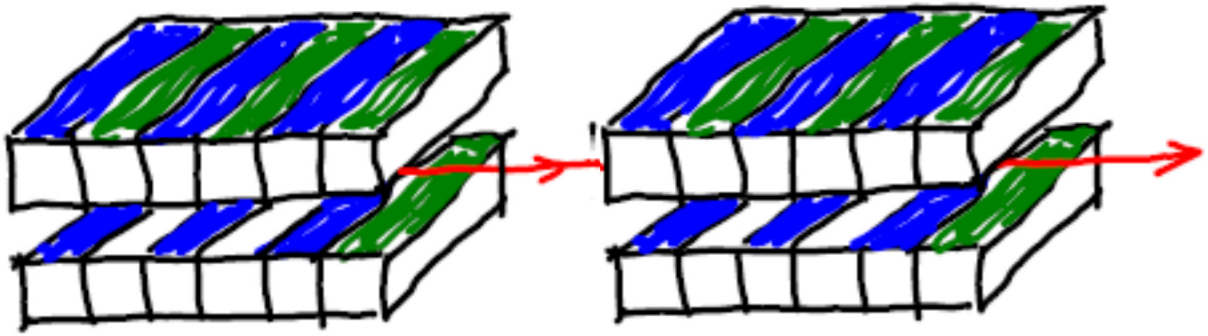
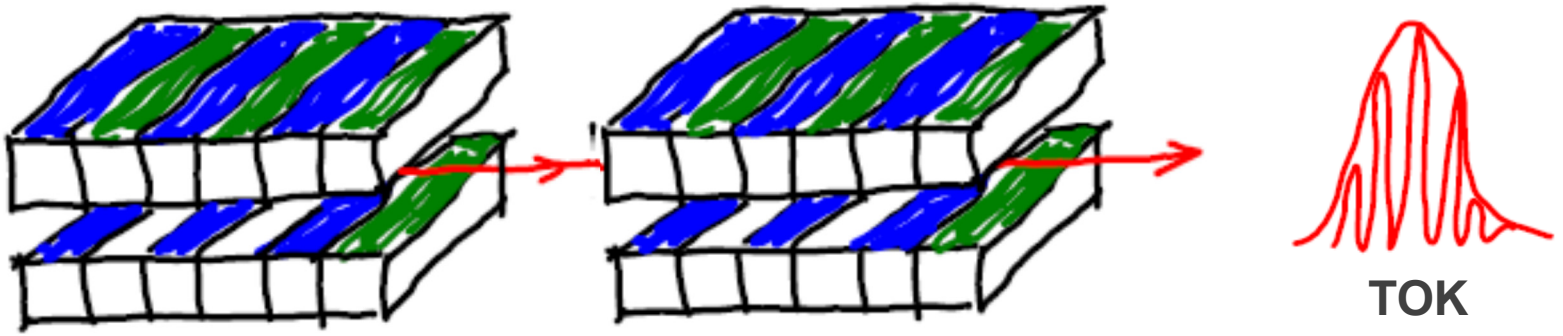
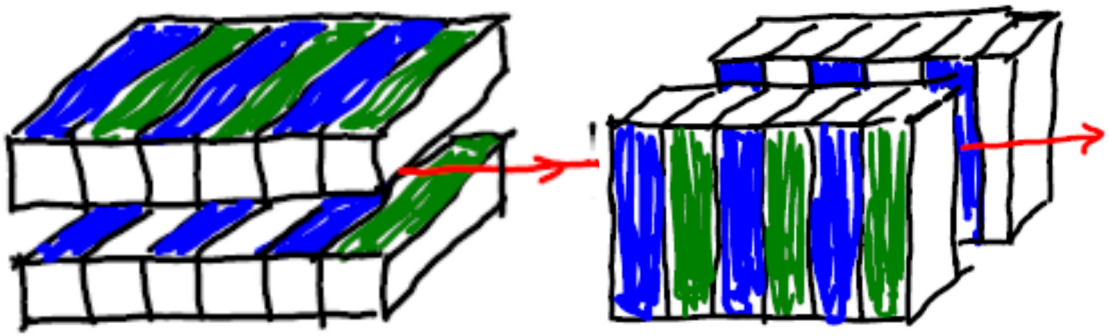
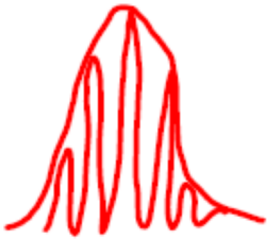


Variable polarization



Variable polarization





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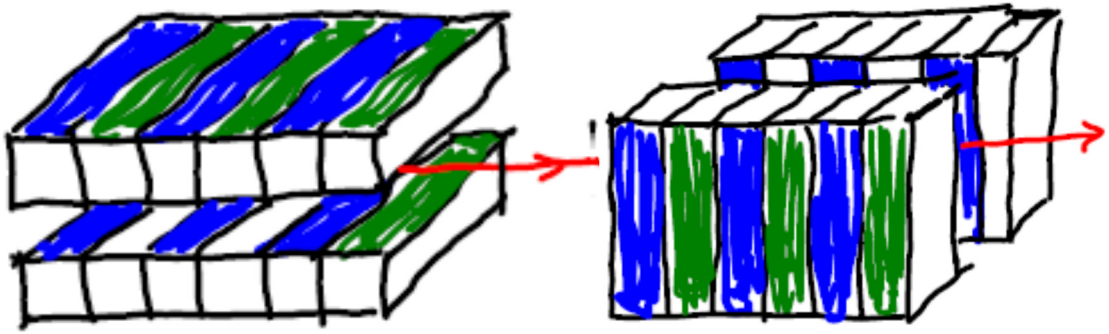

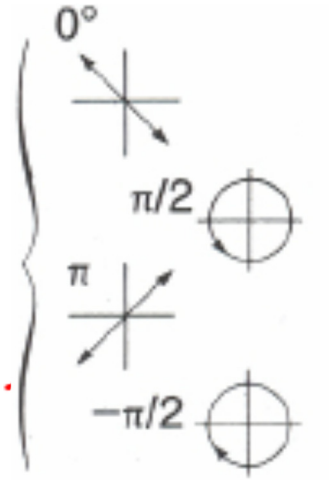

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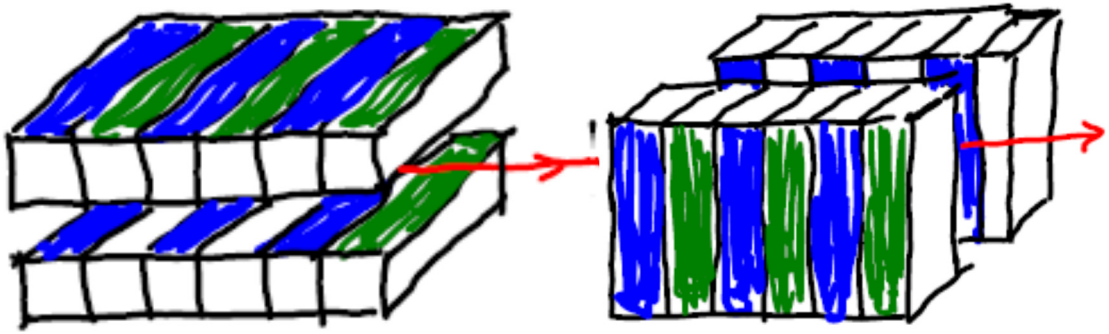
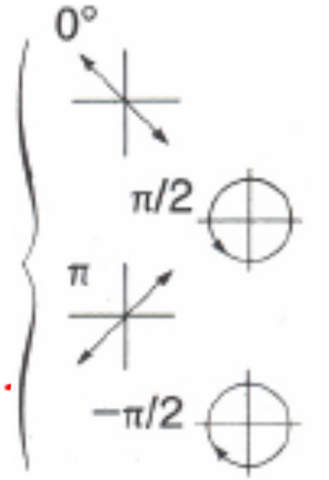




- Eureka moment while listening to Tinoco, a UC Berkeley biochemist at “New Ring’s WS” at Stanford 1983.
- Prototype device at BESSY1 (A. Gaupp and J. Bardt) and at Duke Ring (Ying Wu)
- Ideal for XFELO due to coherence

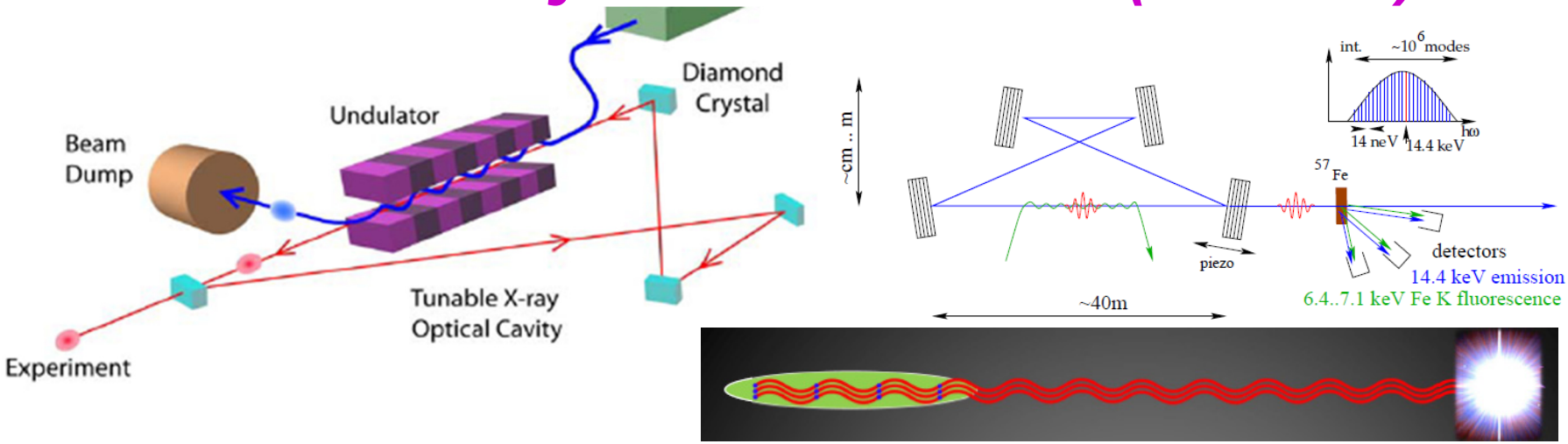
High Gain XFEL Theory Development

- Bonifacio, Narducci, Pellegrini (BNP) proposed SASE as a mirrorless XFEL at 1983 BNL Workshop, independently from earlier proposal by A.M. Kondratenko and E.L. Saldin
- Simplified BNP theory using three collective variables
- 1D Maxwell-Vlasov solved by Laplace transform to include electrons' energy distribution
- 3D analysis taking into account of e-beam 6D distribution via integro-differential eigenmode eq. Initial value problem by Van-Kampen method
- Variational solution by S. Krinsky and L.-H. Yu
- Systematic solution by M. Xie, patterned after Fox-Li for open resonator problem. His interpolation formula greatly expedited the XFEL design

A Short History of XFEL

- The FEL theory was mature by 1990. But it became clear by then that storage rings can not provide the needed longitudinal emittance. (Sag Harbor Workshop)
- How about a linac with a photocathode injector ?
- **My analysis showed that the emittance growth from RF and space charge effect is significant, about 5mm-mr**
- C. Pellegrini, in his seminal talk at 1992 SLAC WS, proclaimed, "***The emittance shall be <1 mm-mrad !*** "
- And so it was! **The emitttance can be compensated, and the LCLS ushered us into the era of x-ray FEL**
- The high-gain XFEL are doing well, with several similar facilities in construction and in operation around the world, novel performance improvement schemes pursued vigorously

The history of XFEL will not be complete without an x-ray FEL oscillator (XFELO)



- Bragg reflectors as suggested at 1983 BNL WS
- Highly stable, fully coherent, ps pulses with ultra-high spectral purity (10^{-7}) with MHz rep rate— **"a real laser"**
- With further stabilization referenced to a narrow nuclear resonance(^{57}Fe), x-ray spectral combs may be generated, allowing experimental x-ray quantum optics for fundamental physics, x-ray metrology, etc

A Short Lesson in Korean and Chinese (the latter from Yuen T. Lee)

- **Kwang (광, 光)--light**
- **Je (제, 齊)– ordered**
- **Kwang-Je → *Coherent Radiation***

Some random samples of pictures

The quest for higher brightness has given me opportunities to meet teachers, colleagues, and students, and excuses to visit many nice places around the world.

Thank you all for intellectual excitement and for good times!